Moored Observations of Nonlinear Internal Waves near DongSha

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LONG-TERM GOALS

I am interested in the general problems of internal waves and the ocean mixing. Knowledge of these is important for advancing the performance of operational and climate models, as well as for understanding local problems such as pollutant dispersal and biological productivity. In the specific case of this DRI's focus, nonlinear internal waves (NLIW), the waves' currents and displacements are strong enough to impact Navy operations such as diving, ROV operation and mine detection/removal.

OBJECTIVES

- To understand the generation mechanisms, and predict the arrival times, of large NLIW in the northeastern South China Sea (SCS).
- To observe NLIW packets and estimate their energy and energy flux in the 2007 South China Sea experiment.
- To relate these to the energy and energy-flux in the low-mode tide, and to measurements of overturn-inferred turbulence.

APPROACH

Two moored profilers and an ADCP will be deployed near DongSha Island, where the waves are most intense. The former will measure internal-wave energy flux, and the latter will measure NLIW energy. These observations will be closely coordinated with other moored observations (Lien, Tang), shipboard echosounder/CTD/T-chain measurements from *R/V OR1* (with Lien and Pinkel) and microstructure measurements from *R/V OR3* (St. Laurent).

To build intuition and to guide experiment design for the 2007 South China Sea experiment, we undertook a data mining study of moored data collected during the ASIAEX experiment. Using simple techniques, we find that the arrival times of the NLIW in the western SCS, and key aspects of their temporal spacing, can be predicted given knowledge of the barotropic currents at Luzon Strait. Since the experiment is still in the planning stage, we report on these results here, which are in press at JGR. This work was done in collaboration with Dr. Zhongxiang Zhao, who is supported on another project and receives no ONR support.

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WORK COMPLETED

Work completed includes participation in the December 2005 NLIWI meeting in San Francisco, planning of the South China Experiment, initial design of the mooring array, completion of the analysis described below, and publication of analysis in JGR (in press).

RESULTS

Our study was initially stimulated by different patterns in the NLIWs' arrival time in these previous observations. Ramp et al. (2004) divided the NLIW packets at mooring S7 (117°17' E, 21°37' N) on the SCS shelf into type-a and type-b NLIW packets, based on their different characteristics. The type-a NLIW packets arrive with remarkable regularity at the same time each day, 24 hours apart; the type-b NLIW packets arrive one hour later each day. The NLIWs in the type-a packets have greater amplitude than those in the type-b packets. In the pilot study of the ASIAEX, however, no pronounced distinction between type-a and type-b NLIW packets was observed at Y (117°13.2' E, 21°2.8' N) (Yang et al. 2004) (Fig. 1).

Large-amplitude NLIWs observed near DongSha Island originate in tide-topography interactions at Luzon Strait. We hypothesize that the different patterns in the NLIWs' arrival times at S7 and Y are a direct consequence of the temporal feature of the barotropic tidal forcing at Luzon Strait. First, we investigate their arrival times with respect to model-predicted barotropic tidal currents (Egbert and Erofeeva, 2002) over Lan-Yu ridge at Luzon Strait. We find that each NLIW packet on the SCS shelf can be associated with a specific westward tidal current peak. The time lags between the NLIWs and the barotropic tidal currents are 57.6±0.9 hours at S7 and 55.1±1.0 hours at Y, consistent with mode-one internal waves propagating nondispersively through the region's bathymetry and climatological stratification (Teague et al., 1990). We obtain a skillful predictor of the NLIWs' arrival time (Fig. 2).

These patterns allow us to speculate on the NLIWs' generation mechanism. The observation that the NLIWs are associated with westward tidal currents, with/without the presence of earlier eastward tidal currents suggests that they are generated by nonlinear steepening of internal tides, rather than by the lee-wave mechanism. We build a simple model: a) these NLIWs are generated by the internal tides emanating from Luzon Strait; b) the internal tides are subjected to nonlinear steepening while propagating in the northeastern SCS; c) after a certain distance, the NLIWs are fully developed in the internal tide troughs and travel faster because of their nonlinear wave speed; d) to the west, the NLIWs outdistance the internal tide troughs. At S7, larger NLIWs usually arrive earlier than smaller ones, consistent with the theoretical relation between nonlinear wave speed and wave amplitude. Based on this observation, the idealized nonlinearization distance is estimated to be 260±40 km from Luzon Strait (Fig. 3).

To summarize, we find that:

1. Each NLIW packet near DongSha can be associated with one westward tidal current peak at Luzon Strait, with a time lag between them indicating the approximate travel time. The arrival times of the NLIWs at S7 (57.6±0.9 hours) and Y (55.1±1.0 hours) are consistent with those estimates for the mode-one internal wave propagating through the basin's bathymetry and climatological stratification field.

2. Ramp et al. (2004)'s classification of the NLIWs into type-a (larger; every 24 hours) and type-b (smaller; every 25 hours) can be explained by the daily inequality of the barotropic tidal currents at Luzon Strait. This temporal feature is kept in a causative chain of events from tide-topography interactions at Luzon Strait, via trans-basin internal tides, to large-amplitude NLIWs near DongSha.

3. The NLIWs are associated with westward tidal currents, with/without the presence of earlier eastward tidal currents, suggesting that they are generated through the nonlinear steepening of internal tides, rather than through the lee-wave mechanism.

4. Larger NLIWs arrive at Dongsha earlier than smaller ones, consistent with their expected faster propagation speed. Based on this observation, we estimate the "nonlinearization distance", over which the NLIWs develop by nonlinear steepening of internal tides, to be 260±40 km, consistent with previous observations in satellite images.

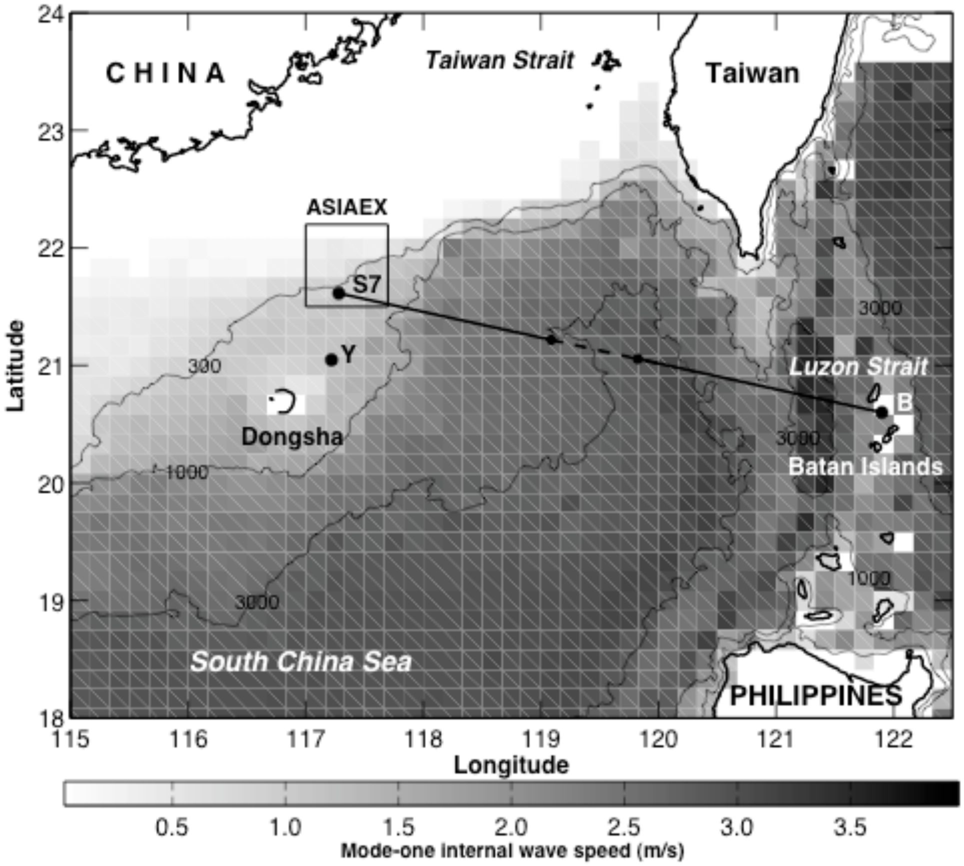

Figure 1: Map of the northeastern South China Sea, showing locations of the ASIAEX 2001 as well as the moorings S7 and Y. The black contours are the isobaths of 300, 1000 and 3000 m. The central location of the Batan Islands is labeled as B, where the barotropic tidal currents are predicted using OTIS. The gray scale shows the mode-one linear wave speed, calculated from climatological ocean stratification profiles in April. The dashed-line section along B-S7 indicates the location where NLIWs become fully developed.

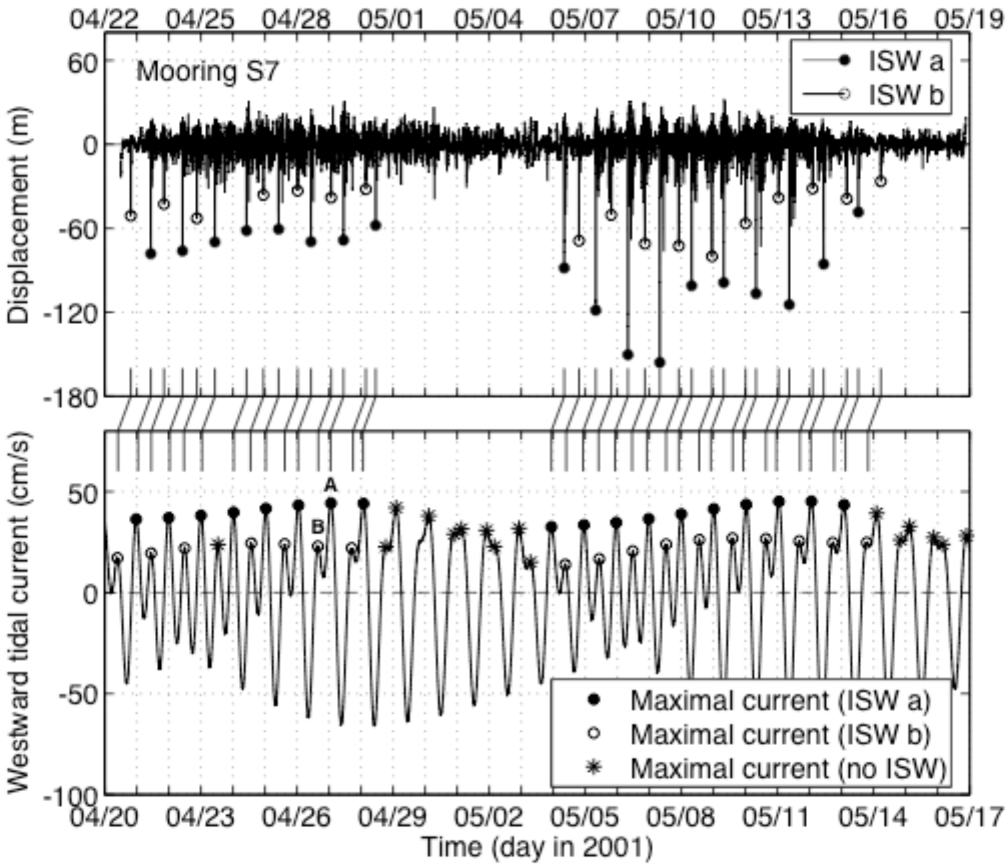

Figure 2: Comparison of the 35 NLIWs at S7 and the corresponding westward tidal current peaks at B. (upper panel) The high-frequency component of the 21°C isotherm displacements. The dots and circles indicate the type-a and type-b NLIWs, respectively. (lower panel) The model-predicted barotropic tidal currents at B. The asterisks are the westward tidal current peaks without NLIWs. Note that the start time is April 22 in the upper panel and April 20 in the lower panel.

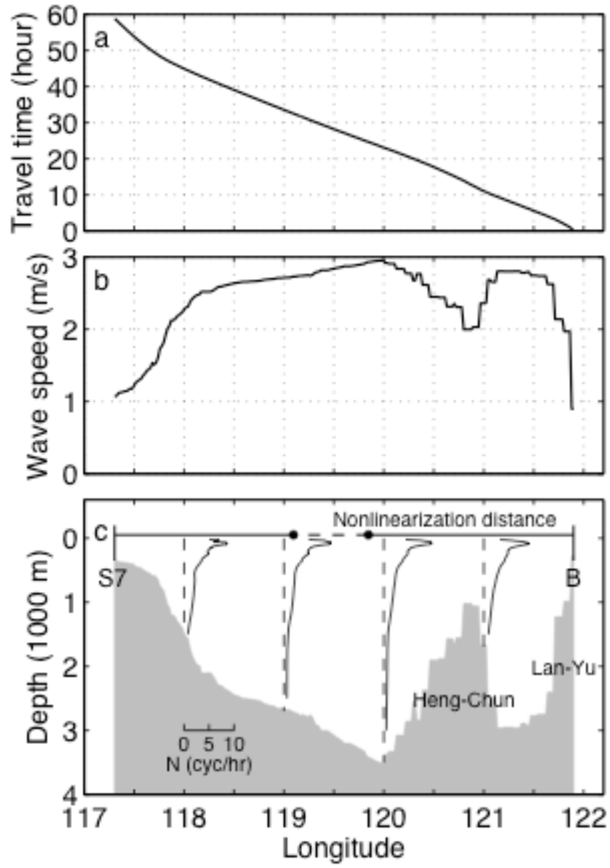

Figure 3: (a) Propagation time of internal tides along section B-S7, calculated from the mode-one linear wave speed. (b) The mode-one linear wave speed profile in April. (c) Bottom profile along section B-S7. There are two parallel ridges at Luzon Strait, the Lan-Yu ridge and the Heng-Chun ridge. Four buoyancy frequency profiles at different locations are shown. The nonlinearization distance is also shown.

IMPACT/APPLICATIONS

This study provides the basic components of a simple prediction model. The NLIWs on the SCS shelf are related to the westward tidal currents at Luzon Strait. Their travel time can be estimated from the mode-one linear wave speed. The barotropic tidal currents at Luzon Strait can be accurately predicted from the existing tide models (e.g., OTIS and PCTide). Thus, the arrival times of the NLIWs in the northeastern SCS are predictable. As we showed, the NLIWs' arrival times at moorings S7 and Y can be predicted with RMS error smaller than one hour (Fig. 3).

Due to the lack of in situ measurements in the deep water zone, the detailed generation and propagation processes of the NLIWs are unknown. Therefore, we cannot predict either the amplitude of the NLIWs or the number of NLIWs in a wave packet. The amplitude of the generated NLIWs depends, in addition to the strength of the tidal currents, on the background flow and stratification near the generation region. The varying conditions also likely affect the interaction of the generated waves with the complex two-ridge topography near Luzon Strait. This study's limited ability to predict the amplitude of the waves is an indication of our incomplete understanding of these processes. Field

measurements and numerical models are needed to understand these processes and to build a successful prediction system.

TRANSITIONS

A portion of this work began as Zhongxiang Zhao's PhD thesis at the University of Delaware, and much of the analysis is his. Since the work was closely related to another project, on which he is working as my postdoc, he receives no ONR support on this or other projects.

RELATED PROJECTS

This work will be closely coordinated with other PIs' efforts in this DRI; namely, microstructure work (St. Laurent), other ADCP's (Lien), conventional moorings (Tang, Ramp), as well as other shipboard field studies in 2007. Experiment design and planning will be guided by modeling work and the ASIAEX and SCS05 experimental results.

NSF grants with Drs. Nash and Kunze to examine internal-tide reflection off the Oregon shelf, and with Drs. MacKinnon, Winters Pinkel and Munk to examine long-range internal-tide propagation north of Hawaii, share many goals and techniques with this project.

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PUBLICATIONS

Zhao, Z., and M. H. Alford, Source and propagation of internal solitary waves in the northeastern South China Sea, *Journal of Geophysical Research*, in press.